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Research article

The environmental impact of dairy production on poorly drained soils under future climate scenarios for Ireland

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ABSTRACT

The environmental impact of dairy production in Ireland has been widely studied and it is known that regional differences in management and impact are driven by climate. Climate change projections for Ireland predict increasing temperature, change in rainfall patterns and decreasing in solar radiation, varying by agroclimatic region. This study evaluated the environmental impacts of low-cost, grass-based, rotational-grazing dairy production on poorly drained soils under climate change. The *Dairy_sim* model was used to determine the theoretical optimum dairy system management for five different locations in Ireland assuming a poorly drained soil resource under baseline (1981–2000) and future climate scenarios (2041–2060, high and low emissions scenarios). An optimum system was defined as having maximum grass production and grazed grass in the diet, minimum necessary silage, minimum imported feed, minimum housing days and a very small silage surplus. Life cycle assessment was then used to quantify the environmental impacts (climate change, eutrophication and acidification) for all scenarios. The dairy production systems were predicted to be more productive in the future, with climate change impacts per unit milk reduced or the same, acidification impacts reduced and eutrophication impacts reduced. The absolute emissions driving climate change and eutrophication were predicted to significantly increase for the future low emission scenario, and emissions driving acidification were predicted to slightly increase. The predictions indicate that system adaptation to mitigate absolute emissions are needed rather than just policies that focus on impacts per unit output.

1. Introduction

To meet the demands of increasing global population over the next century, the challenge for agriculture is to increase production in warmer climates and satisfy climate change policy requirements (Cullen and Eckard, 2011). Livestock is currently one of the fastest growing agricultural sectors, projected to increase globally by 80% by 2050 compared with 2005 (Alexandratos and Bruinsma, 2012), but at the same time accounting for 11% of global greenhouse gas (GHG) emissions (Llonch et al., 2016). World milk production is projected to increase by 25% compared to 2013 to 2015 (OECD/FAO, 2016). The Irish Environmental Protection Agency (EPA) estimated an increase of 6% in GHG emissions from agriculture sector mainly in the period 2014 to 2020, due to the Irish dairy expansion (EPA, 2016a). Dairy production is one of the most profitable agricultural enterprise in Ireland (McDonald and Macken-Walsh, 2016), being based on a predominately low-cost, grass-based, rotational-grazing system (O'Brien et al., 2014). As grazed grass is the main source of herd nutrition, dairy production may be vulnerable to climate fluctuations (Kalaugher et al., 2017) compared to systems that rely on imported feed (Clark et al., 2012), and to the water status of the available soil resource (Schulte et al., 2012; Shalloo et al., 2004). Temperature and rainfall influences the length of grazing season and summer soil water deficit influences the stocking rate (Fitzgerald et al., 2005). Solar radiation influences all of these factors to some degree, and is projected to decrease in future (Fealy and Sweeney, 2008). Soil water deficit influences grass grown (limiting when too wet or dry), machine trafficability, animal treading damage and nutrient use efficiency (Schulte et al., 2006). The interaction of climate and poor drainage makes dairy management more difficult due to slower regrowth and recovery after grazing and field events (Drewry, 2006). Around 30% of Irish milk is produced on poorly drained soil (O'Loughlin et al., 2012) so understanding the interaction of poorly drained soils and future climate scenarios has significant implications for both production policy (Food Wise 2025 (DAFM, 2015),) and environmental impacts (EPA, 2016a; EPA, 2017).

Climate is a major factor of any agricultural production system (Kalaugher et al., 2017) and the impacts of climate change are already being seen around the world due to rising temperatures and change in

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precipitation patterns (Pachauri and Meyer, 2014). Evidence of climate change is emerging in Ireland and projections indicate increasing temperature and changes in precipitation spatial and temporal distribution (Caffarra et al., 2013). An increase of 1.0–1.6 °C in mean annual temperature by mid-century is projected, with the largest increase in east of the country, along with a significant decrease in average precipitation (Nolan, 2015). Fitzgerald et al. (2009) predicted that Irish dairy production would be able to adapt to climate change, but the overall effect is also uncertain due to regional variations in resources and climate (Cullen et al., 2009). It is important to better understand how farms with poor soil resources might adapt to climate change as it is some of this land bank that will be needed to produce milk to meet production targets (DAFM, 2015). Grass production is predicted to decrease in the east and increase the west (Holden and Brereton, 2002), but the system is predicted to be able to adapt, even on poorly drained soil (Fitzgerald et al., 2009). The implications of future climate on the environmental impacts of dairy based systems in Ireland had not been studied.

The approach taken for this work was to use a mechanistic simulation model to find an optimum system of management for a given soil and climate combination, and to then use the model output as activity data for a life cycle assessment to calculate environmental impact. Farm level models have been used to evaluate GHG emissions from dairy farms under future climate scenarios (Cullen and Eckard, 2011; Del Prado et al., 2013; Rotz et al., 2015) and life cycle assessment (LCA) is widely used to evaluate the environmental impacts of dairy farms (Yan et al., 2011). A combination of farm level model and LCA have been previously used for evaluating environmental impacts of livestock sector in the UK (Chatterton et al., 2015).

In comparable temperate areas studies have indicated different trends. For New Zealand, a projected 18% decrease in average annual grass production was reported under climate change scenarios which was interpreted as having a negative impact on pasture based dairy production (Kalaugher et al., 2017). A similar study showed an increased productivity of dairy farms in the UK (Del Prado et al., 2009). This study also reports a decrease in GHG emissions and increase in acidifying gases and nitrate leaching. There is evidence that the impact of climate change will vary regionally (Kalaugher et al., 2017; Shrestha et al., 2014) and will depend on the time scale and spatial extent of the study area (Del Prado et al., 2009).

The aim of this study was to evaluate the future environmental impacts of milk production in Ireland subject to climate change and the worst case scenario of production on poorly drained soil. Dairy production was modelled as theoretical dairy units in different agro-climatic regions in Ireland (Holden and Brereton, 2004) using the *Dairy_sim* system simulation model (Fitzgerald et al., 2005, 2008) and the environmental impact quantified using the dairy LCA model of Sharma et al. (2018).

2. Materials and methods

2.1. Dairy system optimisation and location

A typical Irish spring calving, low-cost, grass-based, rotational-grazing dairy system (Sharma et al., 2018) assuming poorly drained soil was modelled at five locations in Ireland. The starting point for all the farms was assumed to be a 20 ha dairy unit with 40 lactating cows (2 live unit/ha, in compliance with the Good Agricultural Practice Guidelines (EU, 2014)), producing 5545 kg milk/year (Chen and Holden, 2017). Housing date, live weight, dates for closing of paddocks for 1st and 2nd and 3rd cut for silage were taken from Sharma et al. (2018) for poorly drained soils. The study used the same sites as Sharma et al. (2018) (i) east Co. Cork (Fermoy), (ii) south west Co. Offaly (Birr), (iii) west Co. Clare (Kilmaley), (iv) northeast Co. Cavan (Ballyhaise) and (v) central Westmeath (Mullingar). The *Dairy_sim* model (Fitzgerald et al., 2005) was then used to find optimum farm management at each location using daily climate data, soil type (poorly drained soil) and farm activity data. *Dairy_sim* had been previously tested for well-drained soil (Fitzgerald et al., 2005), poorly drained soils (Fitzgerald et al., 2008) and artificially drained soil (Sharma et al., 2016). The optimisation target was to maximise grass production and utilisation with minimum housing days and neither surplus nor deficit of silage production (Fitzgerald et al., 2009). As *Dairy_sim* does not allow dairy cows and machinery to access fields under wet conditions, poaching damage from grazing and soil compaction from machinery was not simulated. In *Dairy_sim*, poorly drained soils were defined using soil drainage class as defined by soil moisture deficit (SMD) model described in Schulte et al. (2005) and Schulte et al. (2015). The parameters of the model were defined by SMD_{max}: maximum possible soil moisture deficit, SMD_{min}: extent to which soil can saturate water, SMD_c: soil moisture deficit at which grass begins to experience water stress and $Drain_{max}$: maximum drainage rate in mm/day (Schulte et al., 2005). The values for poorly drained soils in the model were: $SMD_{max} = 110$; $SMD_{min} = -10$; $SMD_c = 10$ and $Drain_{max} = 0.5$ mm/day (Schulte et al., 2005, 2015).

2.2. Future climate scenarios

Global Climate models (GCMs) are widely used to predict future climate, but with a relatively coarse grid they are not suitable for making predictions at local level (Fitzgerald et al., 2009). There are two methods of downscaling the data: (i) statistically downscaling as used in previous studies to provide future predictions (Fealy and Sweeney, 2008) and (ii) dynamical downscaled used in recent studies, which provide very high resolution data in Ireland (Nolan et al., 2017; O'Sullivan et al., 2016). The later studies have used a combination of GCM and high resolution regional climate models (RCM) to predict future climate data, which exhibits greater variability over Ireland than statistically downscaling methods (O'Sullivan et al., 2016).

The climate scenarios used for this study (summarized in Table 1) were developed for the ensemble of regional climate model projections for Ireland by the Irish Environmental Protection Agency (Nolan, 2015) using two high resolution dynamically downscaled regional climate models (RCM), within a set of two global climate model (GCM) simulations. The RCMs used for this work were Consortium for Small Scale Modelling, Climate Limited Area Modelling model (CLM4) and the Weather Research and Forecasting (WRF) model. The GCMs used were Hadley Centre Global Environment Model version 2 Earth System configuration: HadGEM2-ES and the EC-Earth consortium.

The fields were generated using most recent Representative Concentration Pathway (RCP) 4.5 and 8.5 emission scenarios to generate data for two time periods 1981 to 2000 (baseline period) and 2041 to 2060. Thus there were three cases: baseline, low emission and high emission. These periods were chosen as these were the longest decadal time period common for the simulations. RCP4.5 is a medium- to low-emission and RCP8.5 is a high-emission scenario. RCP4.5 and RCP8.5 are the most recent emission factors recommended by IPCC (Pachauri and Meyer, 2014). A different number of runs and slightly different initial conditions were used for each GCMs. The GCM outputs

Table 1
Details of all the simulations used, the driving GCM/RCM, the RCP and number of realisations (running the same GCM with slightly different conditions) for historical (1981–2000) and future (2041–2060) used for future climate data.

Driving GCM	RCM	Number of realisations
HadGEM2_ES	CCLM4	Historical (1) RCP4.5 (1), RCP8.5 (1)
EC-Earth	CCLM4	Historical (3) RCP4.5 (3), RCP8.5 (3)
EC-Earth	WRF	Historical (3) RCP4.5 (3), RCP8.5 (3)

were on a very coarse grid of 4–6 km. For more details regarding these projections see Nolan (2015). The climate data projected from these combinations of GCM and RCM are robust for Ireland (Nolan et al., 2017; O'Sullivan et al., 2016). Daily maximum and minimum temperature (° C), daily precipitation (mm/day) and global radiation (MJ/m^2/day) were used as a climate data input for *Dairy_sim*. Where the global radiation field was not available (HadGEM2_ES/CCLM4 and EC-Earth/CCLM4, GCM/RCM simulations) it was estimated from daily duration of bright sunshine (h/day), the day length, (h/day) and extra-terrestrial radiation using the Angstrom formula and calculations described by Allen et al. (1998) and parameter values a = 0.21 and b = 0.67 from Fealy and Sweeney (2008).

2.3. Life cycle assessment

The goal of the study was to assess the environment impacts of low cost grass based dairy production in Ireland on poorly drained soil subject to climate change because of the national policy focus on agricultural production and climate change mitigation. It was intended that the study could be used to make recommendations about adaptation potential and impacts of dairy production on poorly drained soil. The system boundary was from 'cradle to farm gate' and was consistent with that described by Sharma et al. (2018) (Fig. 1). The functional unit (FU) was 1 kg of energy corrected milk (ECM) at the farm gate as calculated by Sharma et al. (2018). Fat and protein content were assumed to be 3.94% and 3.4%, respectively (Hennessy et al., 2013).

The outputs of *Dairy_sim* were used for the foreground inventory. On farm processes were: cattle housing and milking unit, manure storage and spreading, grass and silage production and fertiliser spreading. The off-farm processes were: replacement heifers (18% replacement rate, (O'Brien et al., 2012), production and transport of fertiliser and concentrates, production of electricity and diesel. The amount of P and K fertiliser use was taken from Chen and Holden (2017) and the manufacturing process from the Gabi 6.0 database (Thinkstep, 2014). The allocation between dairy and non-dairy activities (production of heifers for sale and culled cows), was based on energy and protein requirement, and was taken as 88% for milk (O'Brien et al., 2012). All the emissions calculations (Table 2) and further details about the system can be found in Sharma et al. (2018). The impact assessment method was CML 2001. The Climate change (CC, kg $CO_{2\text{-eq}}$), acidification (AP, g $SO_{2\text{-eq}}$) and eutrophication (EP, g $PO_{4\text{-eq}}$) impacts were chosen because they directly relate to international and national environmental policies.

2.4. Data analysis and comparisons

Dairy simulation results were summarized on an annual basis with results presented as a mean for 20 year simulation of each climate scenario at all locations. The environmental impacts were then calculated for each of these optimised farms, i.e. 7 systems for baseline and 14 systems for future (7 low emission and 7 high emission) scenarios for each location. The results from *Dairy_sim* and the LCA model was then used to calculate average and standard deviation for each location to compare scenarios. ANOVA single factor was used to assess the null hypothesis of no significant difference between baseline and the future scenarios for each location.

3. Results

3.1. Farm management

The optimised system for each location is summarized in Table 3. For baseline, the mean stocking rate was 1.65 LU/ha. For the future low emission scenario the mean stocking rate was 1.73 LU/ha and for the high emission scenario it was 1.70 LU/ha. For the baseline scenarios, the stocking rate was lowest for Ballyhaise and for future scenarios it was lowest for Kilmaley. The stocking rate was highest for Birr for all the climate scenarios. The mean grass production from the sites were around 8.5 t/ha/yr for both baseline and future climate scenarios. The mean grass production was lowest for Kilmaley and highest for Birr for all the climate cases. The mean housing days for baseline were 181 days vs 161 days for the future scenarios. The housing days were least for Fermoy and highest for Ballyhaise for the climate scenarios.

3.2. Environmental impacts

The mean and regional variation across all the locations (Table 4), showed that CC ranged between 1.13 and 1.19 kg $CO_{2\text{-eq}}$ baseline. For the future low emission scenarios, the CC ranged between 1.12 and 1.18 kg $CO_{2\text{-eq}}$ and for the high emission scenarios, CC ranged between

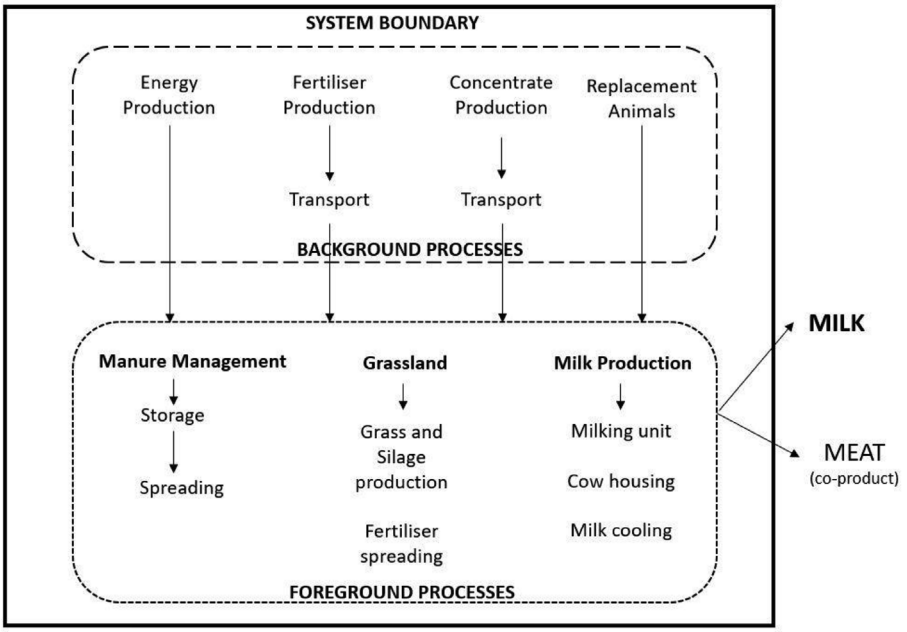

Fig. 1. System diagram of modelled dairy farms indicating cradle to farm-gate system boundary, foreground and background processes.

Table 2
Emission factors used in LCA model to calculate environmental impacts.

Emissions and Source	Factor	Unit	Reference
Methane (CH_4)			
Enteric[a]	106.2–10.2	kg CH_4/cow/year	(O'Mara, 2006)
Manure storage[a]	15.9–24.8	kg CH_4/cow/year	(O'Mara, 2006)
Slurry spreading[b]	6.8–12		(Chadwick et al., 2000)
Nitrous oxide (N_2O)			
Direct N_2O grass paddock[c]	0.01	N_2O-N/kg N	(IPCC, 2006)
Indirect N_2O grass paddock[c]	0.01	kg N_2O-N/kg NH_3-N [d] NO_x-N volatilised	(IPCC, 2006)
Nitrate leaching grass paddock	0.3	kg N_2O-N/kg N leached	(IPCC, 2006)
Direct N_2O manure storage	0.002 (slurry storage) 0.005 (solid manure storage)	N_2O-N/kg N	(IPCC, 2006)
Indirect N_2O manure storage	0.01	kg N_2O-N/kg NH_3-N [d] NO_x-N volatilised	(IPCC, 2006)
Nitrate leaching manure storage	0.3	kg N_2O-N/kg N leached	(IPCC, 2006)
Ammonia (NH_3)			
Cattle housing Unit[a]	38.2[b]	g NH_3-N/cow/day	(Duffy et al., 2011)
Milking unit	7.3[d]	g NH_3-N/cow/day	(Duffy et al., 2011)
Grass paddock	0.2[a] N excreted	g NH_3-N/cow/day	(IPCC, 2006)
Manure storage	94[a]area solid manure storage	g m^{-2} over 30 days	(Duffy et al., 2011)
FYM spreading	0.81 of TAN applied	kg NH_3-N/kg TAN	(Duffy et al., 2011)
Slurry spreading	0.37–0.60 of TAN applied	kg NH_3-N/kg TAN	(Duffy et al., 2011)
Fertiliser spreading	1.6%[a]CAN applied	kg NH_3/kg N	(Hyde et al., 2003)

[a] Range for regional factors.
[b] Includes emissions from slurry store below the slats.
[c] Includes emissions from manure excreted, organic and inorganic spreading on grassland.
[d] Emissions from cow collecting yards during milking over lactating period (305 days).

Table 3
Regional variations in farm characteristics (average of 20 years; mean of different GCM/RCM and number of realisations) for baseline (1981–2000) and future low and high emission (2041–2060) climate scenarios.

Parameter	Unit	Kilmaley	Fermoy	Ballyhaise	Birr	Mullingar
Baseline case						
Cows	nos.	33	33	32	35	33
Grass Production	kg/ha	8.4	8.4	8.5	8.9	8.6
Housing days	nos.	178	175	191	179	183
N Fertiliser input	kg/ha	195	192	194	196	195
Grass intake	kg/cow/yr	2127	2102	2070	2049	2083
Silage intake	kg/cow/yr	2423	2425	2485	2462	2423
Concentrate intake	kg/cow/yr	556	572	524	556	542
Future low emission case						
Cows	nos.	34	35	34	36	35
Grass Production	kg/ha	8.3	8.5	8.5	8.8	8.5
Housing days	nos.	165	161	171	166	165
Fertiliser input	kg/ha	191	193	195	193	195
Grass intake	kg/cow/yr	2159	2115	2106	2079	2075
Silage intake	kg/cow/yr	2348	2386	2410	2418	2418
Concentrate intake	kg/cow/yr	605	633	589	609	621
Future high emission case						
Cows	nos.	33	34	34	35	34
Grass Production	kg/ha	8.2	8.4	8.7	8.9	8.5
Housing days	nos.	165	162	170	165	168
Fertiliser input	kg/ha	194	193	192	194	195
Grass intake	kg/cow/yr	2109	2125	2122	2073	2091
Silage intake	kg/cow/yr	2395	2386	2392	2384	2443
Concentrate intake	kg/cow/yr	625	629	591	611	612

1.13 and 1.17 kg $CO_{2\text{-eq}}$. For all the locations and climate cases the CC was lowest for Birr and Fermoy and highest for Ballyhaise. The absolute CC emissions ranged between 195,573 and 202,797 kg $CO_{2\text{-eq}}$ for baseline scenarios. For future emissions scenarios, absolute CC ranged between 200,991 and 209,307 kg $CO_{2\text{-eq}}$ and 196,882 to 209,405 kg $CO_{2\text{-eq}}$ for low and high emission, respectively (Fig. 2). The absolute CC was lowest for Fermoy with the low emission scenario and for Kilmaley with the high emission scenario. The absolute CC emissions were highest for Ballyhaise for all scenarios. There was no significant difference in relative emissions between the baseline and future climate scenarios ($p > 0.05$). In case of absolute emissions, a significant difference was found between baseline and the low emission scenarios ($p = 0.002$) but no significant difference was found between baseline and the high emission scenarios ($p > 0.05$). The dominant contributor to CC emissions was methane from enteric fermentation, similar to previous studies (Sharma et al., 2018; Chen et al., 2016). The other major contributors were animal excretion, fertiliser production, replacement animals and manure storage.

The mean AP ranged between 5.08 and 5.25 g $SO_{2\text{-eq}}$ for the baseline. For the low emission scenario, the AP ranged between 4.92 and 5.04 g $SO_{2\text{-eq}}$ and for the high emission scenario, AP ranged between 4.94 and 5.02 g $SO_{2\text{-eq}}$. By location and climate scenarios, AP was lowest in Fermoy and highest in Ballyhaise. In the case of EP, it ranged between 2.70 and 2.75 g $PO_{4\text{-eq}}$ for the baseline. For the low emission scenario, EP ranged between 2.66 and 2.69 g $PO_{4\text{-eq}}$ and 2.66–2.70 g $PO_{4\text{-eq}}$ for the high emission scenario. By location and scenario EP was lowest in Birr and highest in Ballyhaise.

The absolute emissions for AP, ranged from 869 to 921 kg $SO_{2\text{-eq}}$ and for EP from 462 to 486 kg $PO_{4\text{-eq}}$ for baseline. For future emission scenarios, AP ranged between 871 and 925 kg $SO_{2\text{-eq}}$ for low emissions and between 848 and 910 kg $SO_{2\text{-eq}}$ for high emissions. The EP ranged from 470 to 496 kg $PO_{4\text{-eq}}$ for low emissions and between 459 and 490 kg $PO_{4\text{-eq}}$ for high emissions. The AP and EP were lowest in Kilmaley and highest in Ballyhaise for all scenarios. The dominant contributor to AP emissions was ammonia from manure storage and application as also reported by Chen et al. (2016). The dominant contributor to EP emissions was nitrate from animal excretion and manure storage as reported by O'Brien et al. (2012). Significant difference was found for both relative AP and EP between baseline and future scenarios. No significant difference was found for absolute AP emissions. In the case of absolute EP, significant difference was found between baseline and the low emission scenario ($p = 0.03$) but no significant difference was found between baseline and the high emission scenario ($p > 0.05$). The largest differences were among baseline and low

Table 4
Environmental impacts per kg energy corrected milk for baseline and future low and high emission climate scenarios: climate change (CC kg $CO_{2\text{-eq}}$), acidification (AP g $SO_{2\text{-eq}}$) and eutrophication (EP g $PO_{4\text{-eq}}$); mean of different GCM/RCM and number of realisations (running the same GCM with slightly different conditions).

Category	Kilmaley	Fermoy	Ballyhaise	Birr	Mullingar	Mean	St. Dev.	p values
Baseline case								
CC	1.15	1.13	1.19	1.13	1.15	1.15	0.023	–
AP	5.13	5.08	5.25	5.12	5.18	5.15	0.067	–
EP	2.72	2.71	2.75	2.70	2.73	2.72	0.019	–
Future low emission case								
CC	1.15	1.13	1.18	1.12	1.15	1.14	0.021	0.23
AP	4.97	4.92	5.04	4.96	4.98	4.97	0.045	1.14E-06
EP	2.68	2.66	2.69	2.66	2.68	2.68	0.014	2.26E-06
Future high emission case								
CC	1.16	1.13	1.17	1.13	1.15	1.15	0.020	0.63
AP	4.99	4.94	5.02	4.94	5.01	4.98	0.036	3.61E-05
EP	2.70	2.68	2.68	2.66	2.70	2.68	0.016	1.69E-03

emission cases for AP and EP.

4. Discussion

The aim of this study was to evaluate the future environmental impact of milk production in Ireland, which was achieved using a combination of system simulation modelling and LCA. The baseline systems for each location were in general agreement with previous studies indicating that the system simulation was adequate for this purpose. In general, the stocking rates were predicted to be higher on poorly drained soils in the future scenarios, which was similar to the results of Fitzgerald et al. (2009). In contrast to the previous studies (Fitzgerald et al., 2009; Shrestha et al., 2014), grass production was predicted to be lower at Kilmaley and Mullingar, while elsewhere grass production was predicted to increase. A longer grazing season was predicted, which is similar to Shrestha et al. (2014), and compared to Fitzgerald et al. (2009), the number of housing days was reduced by a factor between −0.7 and −0.17. Stocking rate increase was less than reported by Fitzgerald et al. (2009) for all the locations and the increase by a factor between 0.02 and 0.06 for this study was less than reported by Sharma et al. (2016) for dairy units on poorly drained soils with artificial drainage. These difference to Fitzgerald et al. (2009) can be attributed to the source of daily climate data (statistical downscaling vs dynamic downscaling, different GCM models), the use of different emission scenarios driving the GCMs and the management data used to initialise *Dairy_sim* prior to finding the optimum system. The current study used dynamically downscaled climate data at a very high resolution for Ireland while Fitzgerald et al. (2009) used statistically downscaled data, and the time period for each study is slightly different. O'Sullivan et al. (2016) reported that when compared to GCM/RCM dynamic downscaling, statistically downscaling predicted a greater increase in temperature for sites over Ireland and less extreme events through the forecasted period. While the trend in grass production was different to previous studies, the increase in productivity was consistent with earlier findings. Fitzgerald et al. (2009) used Special Report on Emissions Scenarios (SRES) compared to RCPs used here, so some effect on the results might be expected (Rogelj et al., 2012). The other reason for this difference could be different management practices for farm optimisation, particularly N fertiliser input (360 kg N/ha vs 195 kg N/ha) reflecting different target production scenarios. *Dairy_sim* has been shown to be a reliable model for finding optimum low-cost, grass-based, rotational grazing dairy systems. The implementation for this study was consistent with previous use and the trends predicted were consistent with theoretical expectation and previous studies using both *Dairy_sim* and other methods. It can be concluded that the derived activity data for the LCA component of the study were satisfactory.

The baseline environmental impacts calculated using the LCA model were similar to those reported for Irish dairy production from a number of sources. The CC/FU values were in range by O'Brien et al. (2014), AP/FU values were similar to those reported by Chen et al. (2016) and EP/FU values were similar to those reported by O'Brien et al. (2012). Direct quantitatively comparison with previous studies was not possible, due to differences in scope, inventory and assumptions, but the values were consistent with data reported for Ireland. The environmental impacts were greater than those reported by Sharma et al. (2018) and less than Sharma et al. (2016) for poorly drained soils because greater milk output per cow was simulated by Sharma et al. (2018) and lower milk output simulated by Sharma et al. (2016). As the environmental impact per FU is partly dictated by output (Belflower et al., 2012) the pattern between studies is consistent and theoretically expected. On average CC/FU was not significantly different between baseline and either low or high emission scenarios indicating dairy production on poorly drained soil will be able to adapt to climate change with no greater adverse climate impact per unit product. The CC/FU values for each location was slightly different due to stocking rate, fertiliser application, number of housing days and feed intake. There is uncertainty associated with soil organic carbon (SOC) loss due to land management practices such as land drains installation (Lilly et al., 2012), which suggests that SOC losses during installation will outweigh gains due to production increase. When combined with the future scenario results, this suggests that installation of land drains may not be desirable from an environmental point-of-view.

The AP/FU significantly decreased for all the locations, by around 3.5% (low) and 3.4% (high), for both scenarios. The EP/FU significantly decreased by 1.8% (low) and 1.4% (high) for both scenarios. The greatest reduction was seen at Ballyhaise for both scenarios. The difference in AP/FU between sites was due to the number of housing days, which was greatest at Ballyhaise causing greater ammonia emissions from housing. The difference in EP/FU was due to nitrate leaching, stocking rate and housing days as previously reported by Sharma et al. (2018). Greater N loss from land drains has been reported (Monaghan et al., 2016), which suggests that land drains are not a suitable option if the quality of water bodies in Ireland is to be maintained in the future. The decrease in AP and EP impact per FU forecast for future scenarios suggests that the adaptation of dairy production to climate change will result in a decrease in acidification and eutrophication impacts per unit milk produced.

While national policy is focused on reducing climate change impact per unit milk produced, there are also important regulatory targets that are associated with total national emissions. These have implication for the agriculture sector in general and dairy production in particular, because it is the dominant sector. Greater absolute emissions predicted for milk production on poorly drained soils will not be compatible with the European Union targets to reduce GHG emissions for the Union as a whole, and for each individual State (European Commission, 2010). The greater predicted emissions were driven by an increase in stocking rate on farms with poorly drained soil under future scenarios. This

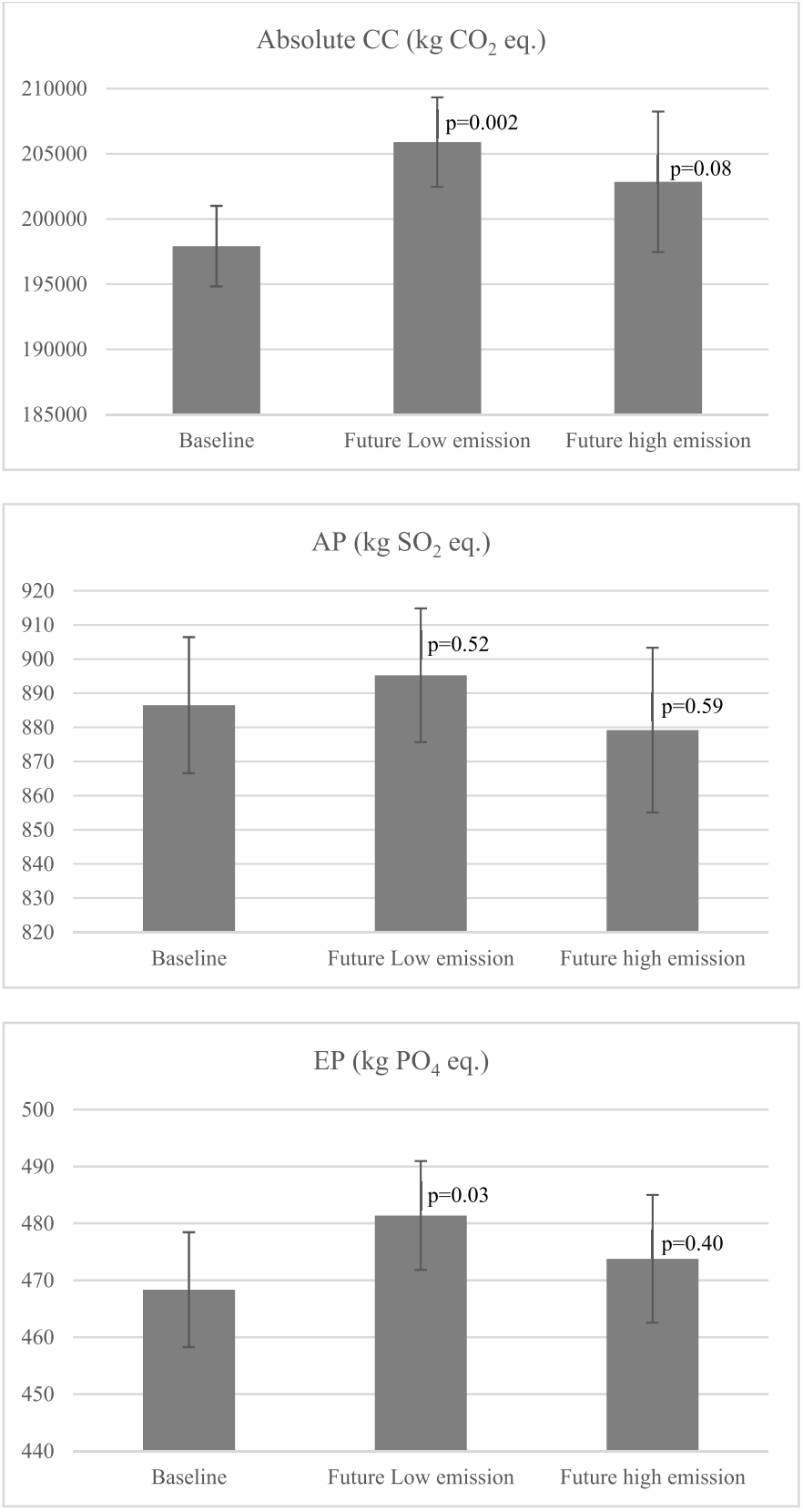

Fig. 2. Absolute mean (five locations) environmental impacts for baseline and future low and high emission climate cases: climate change (CC kg $CO_{2\text{-eq}}$), acidification (AP g $SO_{2\text{-eq}}$) and eutrophication (EP g $PO_{4\text{-eq}}$); mean of different GCM/RCM and number of realisations (running the same GCM with slightly different conditions).

increase is required to maintain the low-cost status of the system (Dillon et al., 2008) and to ensure sward quality year on year (O'Donovan et al., 2011). An increase in emissions by 2015 from the agriculture sector (Bord Bia, 2015) has already been attributed to an increase in the number of dairy cows (EPA, 2016b), and it would appear that even though impact per unit milk will remain similar or decrease, total contribution to Irish emissions will increase. A climate change mitigation and adaptation policy framework is required as suggested by Del Prado et al. (2013) to take actions at the animal, manure, feed production and soil levels. While measures at animal level such as supplementation of lipids in the diet and decreasing dietary protein and at soil level such as nitrification inhibitors can drive perhaps 10% reductions in overall emissions (Del Prado et al., 2010), the predictions from this work suggest that these will be offset by increased animal numbers even on the poorest land for dairy production. No significant increase in absolute AP was predicted, but an increasing trend is likely. An increase in NH_3, which is a major driver of AP from dairy farms (Sharma et al., 2018), coming from manure and chemical fertiliser use, has been reported in Ireland (EPA, 2016b), so policy should ensure that this trend is not allowed to develop as a strong signal. Caps under the National Emissions Ceiling Directive (2016/2284/EU) have helped reduce NH_3 emissions from dairy farms in Ireland so the mitigation solutions to minimise NH_3 emissions from livestock need further attention. These include diet manipulation, covering slurry storage tanks and slurry injection when spreading (Ndegwa et al., 2008). A significant increase in absolute EP emissions was predicted for future scenarios. This suggests that further decline in water quality, which has already been reported in Ireland (EPA, 2017) will occur. The introduction of the Good Agricultural Practices guidelines has reduced N and P surplus on dairy farms in Ireland (Mihailescu et al., 2014, 2015), however more efforts is needed to mitigate N pollution as these measures are not necessarily offsetting the rapid increase in animal numbers. Measures such as optimised soil Olsen P levels and nitrification inhibitors could be used as they are reported to reduce N and P emissions from dairy farms in New Zealand (Monaghan et al., 2008) and in case of field drains, controlled drainage management is reported to reduce nitrate loss (Wesström et al., 2001).

The results of this study reveal that there is a real challenge to understand how to integrate environmental policies and the economics of farm adaptation to climate change. In terms of global market mix, increasing low impact per FU Irish milk would probably be beneficial provided it displaces higher impacts, less efficiently produced milk. In terms of national and regional regulation the focus on impact per FU may be misleading as absolute impacts can be increasing as impact per FU decreases. Solutions to these problems will require further integration of multi-scale and dynamic modelling (Gibbons and Ramsden, 2008) and ecological-economic modelling (Fischer et al., 2005) with LCA and other environmental assessment tools.

5. Conclusion

Taking what is perhaps the worst-case scenario, the environmental impact of dairy production on poorly drained soil, it is clear that the production system can adapt to climate change and the impact per unit milk produced is unlikely to increase for most locations in Ireland. There is however a notable risk that absolute emissions causing these impacts will increase, largely driven by an increase in animal numbers. The role of land drainage in driving impact is not certain and requires further study, along with a more detailed integration of the production and environmental factors with social and economic factors to better understand how to shape policy that is needed to manage agricultural development over the coming decades.

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